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ON THE USE OF HIGH-PERFORMANCE SIMULATION IN THE MANAGEMENT OF GROUNDWATER RESOURCES IN LARGE AQUIFER SYSTEMS

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ABSTRACT

This paper reviews the need for and initial development of an advanced, high-performance computer model of groundwater flow and chemical migration in a large and heavily used groundwater basin in Orange County in Southern California. The objectives of such a model are to provide an improved scientific basis to more fully understand the migration rates, travel times, and overall quality of groundwater throughout the basin, especially as it relates to both historical and future groundwater recharge practices. The use of such a model is dictated by the fine spatial resolution required to examine 3D transport issues over large portions of the simulation domain. It is expected that the ongoing application will demonstrate the viability of applying concepts of large-scale simulation to such a practical and significant problem.

INTRODUCTION

Groundwater has been and continues to be a significant source of domestic water throughout the US and the rest of the world. In California, significant amounts of groundwater are used for both agricultural and urban supplies, despite the fact that the state relies heavily on surface water provided by numerous reservoir and aqueduct systems. As a result of growth, uncertainties produced by drought, environmentally motivated reservoir releases, and the bleak outlook for expansion of the existing reservoir system, many water districts are looking towards the acquisition of new or additional sources of groundwater to augment their water supplies and to provide additional reliability in meeting future water demands.

Increased reliance on groundwater brings a need for improved aquifer management with respect to understanding water mass balances, planning rates of withdrawal and replenishment, balancing the demands and rights of multiple users, and dealing with water quality issues involving salt water intrusion, near surface industrial contamination, and regulatory factors related to recharge and subsequent production of reclaimed water. The purpose of this paper is to review an ongoing application of the ParFlow groundwater flow computer model (Ashby, 1996; Ashby et al., 1996; Tompson, at al., 1996) to the large coastal groundwater basin managed by the Orange County Water District (OCWD) in Southern California. This effort is exploiting modeling capabilities unavailable in most groundwater simulation packages, including, most importantly, the capacity to treat large, complex, 3D problems through the use of parallel computation.

THE ORANGE COUNTY GROUNDWATER SYSTEM

The Orange County Water District manages a groundwater basin that provides 70% of the domestic water supply for approximately 2 million residents in the northern part of Orange County, California (OCWD, 1991, 1995). The remaining 30% is purchased and imported from outside the district. On an average annual basis, roughly 270,000 acre feet (af) of water are extracted from several hundred production wells located within the middle production aquifers of the basin. These units can be over 1,000 ft thick, and generally extend the entire width of the basin, from the so-called Forebay area (under mostly phreatic conditions) toward the confined “Pressure Zone” that abuts the Pacific Ocean and Newport-Inglewood fault (Figs. 1 and 2).

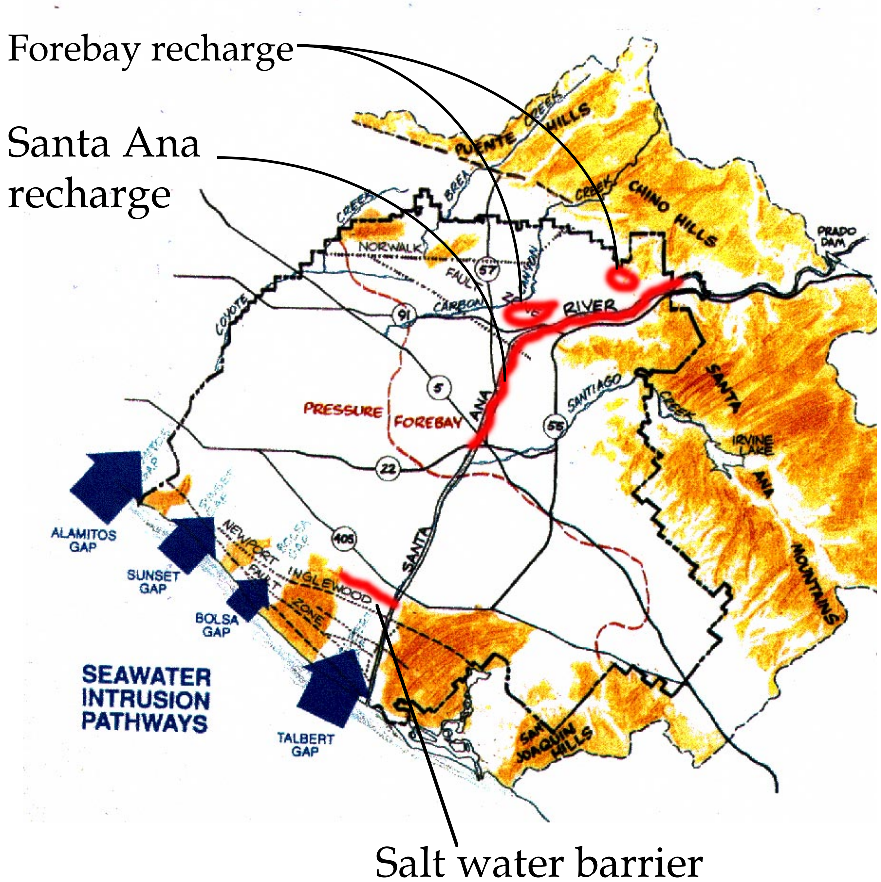

Figure 1: Plan view of the Orange County Water District boundaries (dashed line) showing sea water intrusion pathways, Forebay recharge areas, and the Talbert Gap salt water barrier injection area. The Santa Ana River runs directly through the district for a length of approximately 20 miles (from OCWD, 1991).

To sustain this rate of withdrawal, OCWD maintains an active recharge effort that returns about 205,000 af of water, on an annual basis, to the groundwater basin. This is achieved by diverting large portions of the base flow of the Santa Ana River into a series of infiltration basins and old gravel pits along or nearby the upper reaches of the river (Fig. 1). Water recharged in the Forebay area can easily be drawn into the middle aquifers (Fig. 2), as well as a shallow aquifer in the Pressure zone and a much deeper "colored water" aquifer that is not used for any production.

Near the Pacific coast, OCWD also reinjects roughly 15,000 af of water a year into the shallow aquifer through the so-called Factory 21 saltwater intrusion barrier. This serves to prevent further salt water migration into the middle production aquifers beneath a break in the confining unit (Fig. 2). Because of the faulted structures along the coast, much of the basin is generally protected from significant salt water intrusion.

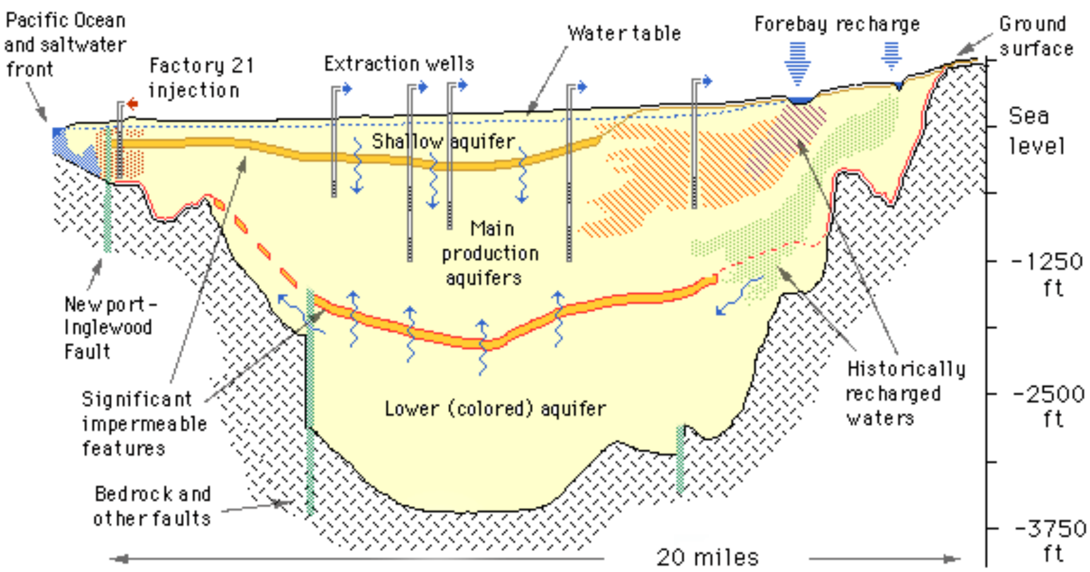

Figure 2: Vertical cross-section of the Orange County groundwater basin, approximately paralleling the Santa Ana River, with the Pacific Ocean to the left. Water recharged in the "Forebay" area (right) can migrate in a southwesterly direction into the main (middle) production aquifers, as well as the shallow and lower aquifers.

BUILDING A GROUNDWATER MODEL

Over the next several years, OCWD expects to accelerate its overall recharge operations so that 100% of the local water demand may be provided from groundwater alone (OCWD, 1991, 1995). By eliminating the need to purchase imported supplies whose availability and cost can rapidly fluctuate, the district seeks to build more reliability into its water supply system. The additional water will be derived from reclaimed water pumped up to the Forebay region from the Water Factory 21 plant located near the saltwater injection barrier. The increased recharge and associated increased production raises three principal concerns for the district: (i) which wells in the basin can produce the supplemental water, (ii) what will be the impacts of additional production on the viability of the existing salt water barrier, and, most importantly, (iii) how will reclaimed water affect overall groundwater quality and potentially affect production? This latter concern revolves mainly around the migration and dilution of the recycled water (portions of which are treated wastewaters) as it enters and mixes with groundwater in the recharge process. Additional water quality issues are concerned with increasing levels of salts (total dissolved solids, TDS) that accumulate in recycled water, certain types of imported water, or from fertilizers, as well as the fate of organic materials that are also recharged into the subsurface. These concerns are exacerbated by the fact that 85% of the base flow in the Santa Ana River already contains discharged wastewaters from growing upstream communities such as Riverside and San Bernadino (OCWD, 1995), implying that their recharge into the OCWD basin has been indirectly occurring for some time.

Proposed regulatory standards in California mandate that treated wastewater recharged into the groundwater remain *in situ* for a period of one year before it can be extracted as a drinking water supply. Moreover, no extraction well can be placed within 500 ft of a percolation basin, regardless of the depth of its screened interval, or within 2,000 ft of a reinjection well.

OCWD has initiated a program to comply with these regulations. Several isotopic techniques are being used to evaluate the source and age of groundwater that is nearby recharge areas, so as to estimate the travel paths and residence times of reclaimed water in the subsurface (Hudson, et al., 1995; Davisson et al., 1996). Figure 3 shows groundwater ages estimated from tritium-helium analyses at several locations near the Forebay recharge basins. Note that the fine layered structure in the sediments appears to promote relatively rapid horizontal flows, while preventing significant vertical flow into the deeper Anaheim production well beneath the Anaheim Lake recharge basin.

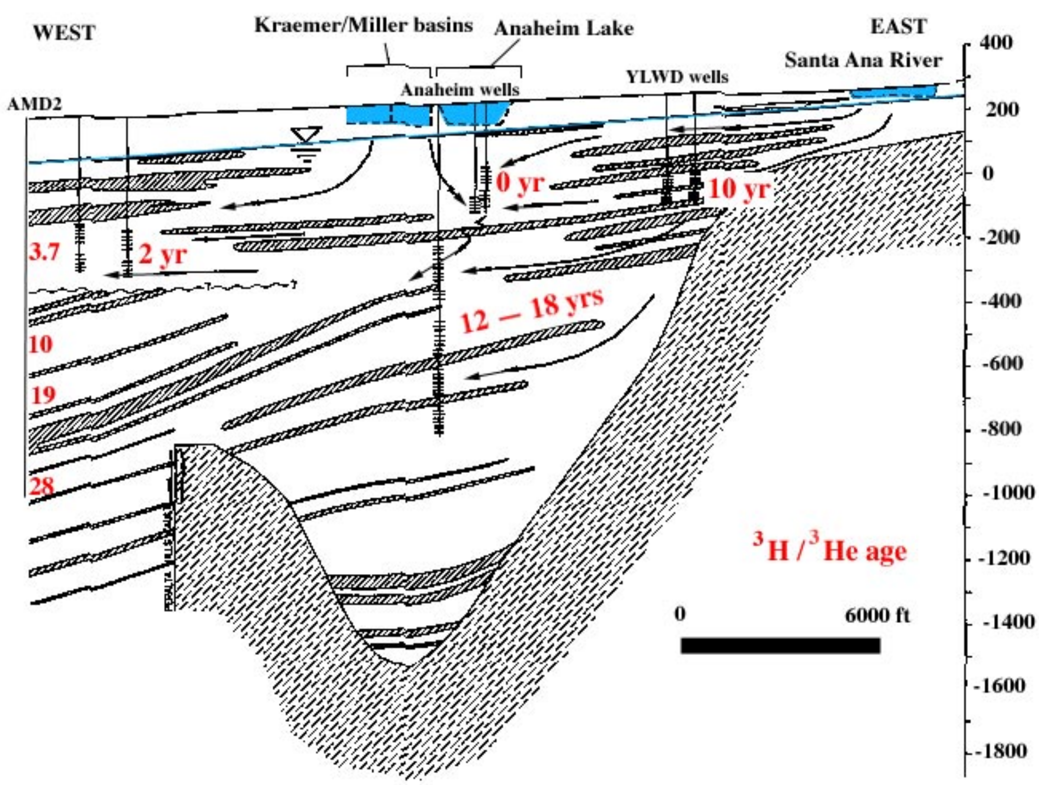

Figure 3: Expanded vertical cross-section beneath the Forebay recharge areas in the Orange County groundwater basin (near the extreme right side of Fig. 2), showing inferred lower

permeability silt layers (dark), estimated groundwater flow paths, and tritium-helium ages measured from various monitoring and production wells (after Davisson et al., 1996). Vertical scale is in feet above seal level.

OCWD has also initiated the development of a 2D numerical groundwater model of their principal production aquifer (as shown in Fig. 2). As such, it will provide a coarse, vertically-integrated representation of groundwater flow that can be used to understand basic water mass balance and travel- or residence-time issues. In collaboration with OCWD, we have initiated the development of a more resolved, 3D model of the entire basin that includes the shallow, main production, and lower (colored) units. In our application, we seek to provide a basis to examine current and future production scenarios from all units, as well as various water quality issues associated with the migration rates, residence times, and dilution of reclaimed water, all at a significantly increased vertical resolution such that the detail and structure of properties and flow evident in Figure 3 can ultimately be reproduced.

DETAILED MODELING APPROACH

We are approaching this study by hierarchically increasing the resolution and complexity built into our model. Initial conceptual representations based upon the ongoing modeling, geologic cross sections, and other interpretations made by OCWD will be supplemented with more detailed information and geostatistical representations of the kinds of aquifer heterogeneity shown in Figure 3. In problems such as this, the relevance and importance of heterogeneity is becoming increasingly apparent (Gelher, 1993; Tompson, et al., 1996). Heterogeneity is known to promote detailed, channeled, 3D flows and accelerated dilution behavior that can affect residence times and travel pathways of recharged water (as already measured, Fig. 3), but neither of which can be effectively represented in a coarse 2D model.

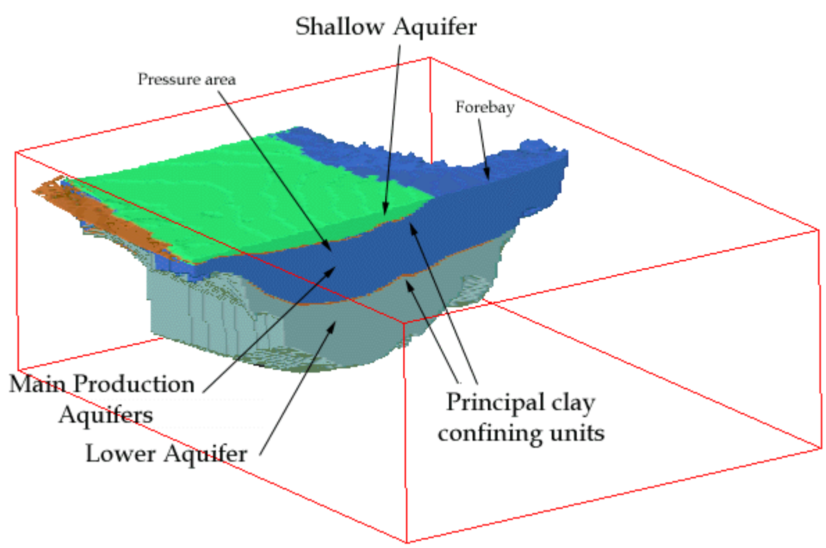

Figure 4: Principal aspects of the 3D model domain used in the ParFlow OCWD application. Major aquifers and confining units are represented as fixed features, in which more substantial geostatsitcal representations are to be later included. Open face corresponds approximately to the

cross section in Fig. 1. This model is based upon 6.6 million nodes and a grid resolution of 200 x 200 x 50 ft.

HIGH PERFORMANCE SIMULATIONS

Our approach for "dealing" with heterogeneity involves the use of ParFlow, a new high-performance groundwater flow model (Ashby, 1996; Ashby, et al.; 1996), to enable highly-resolved simulations of flow and transport phenomena in domains that recreate the character and detail of physical variability observed in natural geologic formations. This can be achieved through the use of multiple, equally-likely stochastic "realizations" of the system heterogeneity within known, or deterministic, structural boundaries of a formation (Tompson, et al., 1996). Each "realization" recreates the spatial variability of measured formation properties or characteristics from a model of heterogeneity, while reproducing specific known data (usually found along borehole transects). The use of repeated "Monte Carlo" simulations allows the uncertainty associated with any one stochastic simulation to be quantitatively bracketed by the results of an ensemble.

The ParFlow model rapidly simulates groundwater flow and chemical migration processes in large-scale, 3D problems through the power of massively parallel computation. Relevant problems in excess of millions or tens of millions of unknowns are easily solved in minutes. The preliminary rendering of the OCWD basin shown in Figure 4 is based upon 6.6 million nodes and a 200 x 200 x 50 ft grid resolution in the two horizontal and vertical directions, respectively.

Aside from basic water balance analyses, detailed simulations will be used to assess travel pathways and residence times of recycled groundwater recharged from the percolation basins, both under historical and future management scenarios. Isotopically determined groundwater ages and recharge sources will be compared with the results of an "ensemble" of model simulations. This will serve both as an aid in model verification and uncertainty assessment as well as a basis for interpreting the isotopic measurements themselves. The interpreted ages are based upon a mean isotopic composition found in a sample taken from a well. As such, they will reflect mixing processes that occur in the sampling procedure, either in the well-bore itself, or as a result of different waters entering a long screened interval of the well. This will tend to oclude the real distribution of ages in the sample. Our approach may allow this distribution to be gauged, so that, for example, the **spectrum** of water ages entering the the deep Anaheim well along its large screened interval (Fig. 3) may be estimated in addition to the **mean** age found in a "normal" sample of well water.

ACKNOWLEDGMENTS

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